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Replacement of Damaged Electrical Insulators on Live Cross-Over Busbars inside a Tunnel: A Methodology based on Risk Assessment and Numerical Simulation

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Abstract

With amperage creep, the cross-over busbars electrical insulation of this smelter was severely damaged by excessive temperatures. Its replacement and upgrade was therefore necessary to ensure safe and continued operation of the potline. Electrical hazards, constrained space, heat stress, strong magnetic fields and poor lighting were amongst the challenges.

This paper details the methodology developed by the project team to solve the issue.

The first success key is that risk analysis was performed at each phase in partnership with the smelter, the original technology supplier and the contractors. The knowledge and experience of the original technology supplier was invaluable in the development of the solution. The second key is that Finite Element Analysis and in situ measurements were used extensively to define an optimized project scope including mitigation measures. The work was then executed with no incident, no damage and no cut-out while on schedule and below budget.

Introduction

The Aluminerie de Bécancour Inc. (ABI) smelter is located on the Saint-Laurent river in the Province of Québec, Canada, and consists of three AP18 potlines, a Carbon Plant and a Casthouse. The cross-over busbars connecting one potroom to the other are running inside a narrow underground tunnel with natural ventilation only. Energy dissipated by the busbars heat up the ambient air until thermal stratification is established and the density gradient becomes sufficient to drive the hot air to escape at the tunnel ends. This low capital cost design had been performing satisfactorily when the potlines operated at its nominal amperage of 180kA.

Unfortunately, it was found in late 2008 that the epoxy grout electrical insulators and the concrete supports of the cross-over busbars were severely damaged, as shown in Figure . The potlines were operating at amperage levels in excess of 209kA at that time. A project was therefore kicked-off to address the issue.

After careful inspection, it was found that busbars were sunk into the insulation and were at different elevations on same support. This suggested permanent deformations, and raised the question of residual stresses in the bars and welds.

Figure – Typical Cross-over Busbar Supports Before Project

Epoxy Grout Performance in Service

As part of a separate study to assess the impact of amperage creep on the potline busbars, a protocol has been developed with an external laboratory to measure the epoxy grout performance in realistic operating conditions. Samples cut from busbar supports were subjected to a compressive load corresponding to the busbars applied pressure while being heated on one face during one week. The samples were thermally insulated to promote unidirectional thermal fluxes. A voltage source was used periodically to measure the leaking current.

It was found that with increasing temperature, the epoxy binder of the grout softens and becomes conductive. The creep rate is also increasing with temperature. At a critical temperature, the grout becomes malleable such that it flows under the compressive stress, as shown in Figure . The binder degradation is irreversible.

At even higher temperatures, the resin binder burns, leaving only ashes. This explained the degradation found on the cross-over busbar supports.

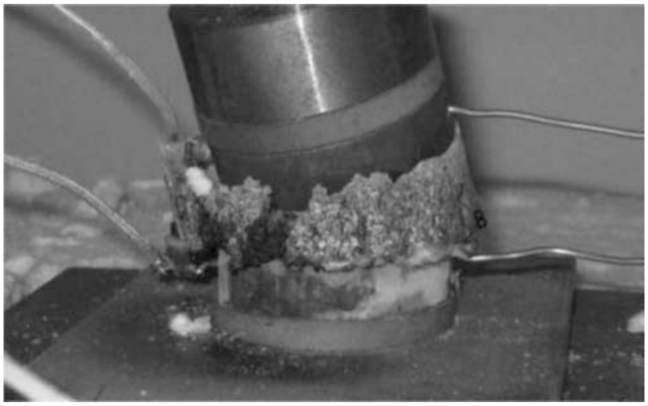

Figure – Epoxy Grout Catastrophic Failure Above Critical Temperature in Laboratory Test

Cross-Over Busbars Temperature

The air escaping the tunnels was measured to be above 100℃ in summer such that the tunnels were inaccessible except in winter. Thermocouples were installed in the tunnels, which revealed busbars temperature frequently above the critical epoxy grout critical temperature, as shown in Figure .

To minimize further electrical insulation degradation, a temporary forced-cooling system was installed. Flexible ducts made of electrically insulating materials were used to blow air directly onto the busbars. Compressed air nozzles were also installed to cool the expansion joint in the middle of the tunnel.

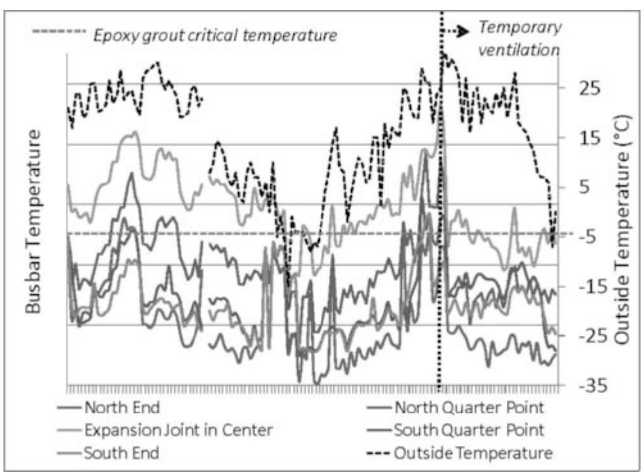

Figure – Cross-Over Busbars Temperature

Solutions Analysis

As part of the Alcoa-Hatch North East Alliance, an integrated ABI-Hatch project team was mobilized to develop options (FEL2 engineering phase) to solve the electrical insulation issues at the cross-over busbars. A separate project was launched to provide permanent forced-cooling to the cross-over busbars in the tunnels with a view to support further amperage creep.

The scope of the insulator replacement project included some supports outside the tunnel but excluded the potroom input and output circuits. It was obviously out of the question to shutdown the potline to execute the work, so all solutions had to be feasible on live busbars.

The original technology supplier, Aluminium Pechiney (AP), was involved in the development of the options given their invaluable experience and expertise with similar problems.

Given the conditions in the tunnels, it was necessary to minimize the amount of work required inside the tunnels. The project team together with AP quickly converged on the concept of lifting the busbars, removing the damaged supports, and placing new prefabricated supports with preinstalled electrical insulation at the proper elevation. AP confirmed that this had been done successfully at another smelter. AP developed basic engineering level (FEL3) drawings and specifications for the electrical insulators and prefabricated support, based on extensive experimental work to certify the insulators and their assembly to the supports in representative operating conditions. Guidelines for busbars lifting procedures were also given by AP based on previous numerical modeling.

Simplified Finite Element Analysis using 1D beam elements was used by the project team to assess the impact of lifting the busbars inside and outside the tunnel on the rest of the busbar systems connecting the last pot of one room to the first pot of the other. It was found that interfaces between the cross-over busbars and the potroom input and output circuits would experience a significant increase in stresses due to bending and torsion loads when lifting busbars outside the tunnel.

Risk Assessment

Formal risk assessment and analysis was performed at each phase of the project in close partnership with experienced engineers from the smelter, and with the contractors. The input of AP and Alcoa expert regarding technical and execution risks was also significant. The risk analysis process would start by a review of the project scope and relevant documentation (drawings, specifications, etc) followed by the development or update of the risk register, the evaluation or update of the probability and consequence for each risk, and then the ranking of the risks according to the combination of probability and risk. Risks exceeding a critical value require mitigation measures that were developed and included in the project scope. The risks were then reassessed after mitigation until all intolerable risks were controlled. The most important risks were obviously the health & safety risks for the workers, summarized in Table . The main technical risks are summarized in Table .

Table – FEL2-Level Health & Safety Risks and Mitigation

Risk	***Mitigation***
Electrical hazards	- *Use of Potline Grounding cart with alarm box at work site* - *Use of battery power tools or compressed air with electrically insulating air hoses* - *No electrical cord tolerated* - *Busbar face exposed to workers is covered by electrical insulation* - *Electrical insulating mats used on work zone floor* - *Use of 1000V rated dielectric gloves for work with direct busbar contact*

Risk	Mitigation
	- *Floating potential specialised tooling*
Constrained space	- *Small work crew in tunnel* - *Use of radio communication devices* - *Specialized tooling for handling of new busbar supports* - *Emphasis on work place cleanliness*
Heat stress	- *Work planned in spring* - *Temporary ventilation put back in function during night time* - *Heat stress protocols followed*
Strong magnetic fields	- *Use of hand tools made of non-magnetic material* - *Specialized tooling built of non-magnetic material*
Poor lighting	- *Use headlamps* - *Additional battery powered fixed lights*

Table – FEL2-Level Technical Risks and Mitigation

Risk	Mitigation
Movement of busbars while lifting due to residual stresses	- *Low friction material in contact with busbars during lifting* - *Large bearing surface on ground* - *Lateral supports for busbars* - *Create fixed point to force displacements towards expansion joint*
Damage busbars or welds while lifting	- *Use numerical simulation to develop optimal lifting sequence and method* - *Develop contingency plans : prepare emergency pre-packaged weld plates kits and have all tools required for repairs on site and qualified welders ready on short notice (1h)*

As mentioned before, the busbars sunk into the insulation at different elevations on the same support raised the question of permanent deformation, residual stresses and the reaction of the busbars when lifted. Moreover, to clear the old supports during the replacement, the bars on a support had to be lifted above the level of the highest bar, as shown in Figure .

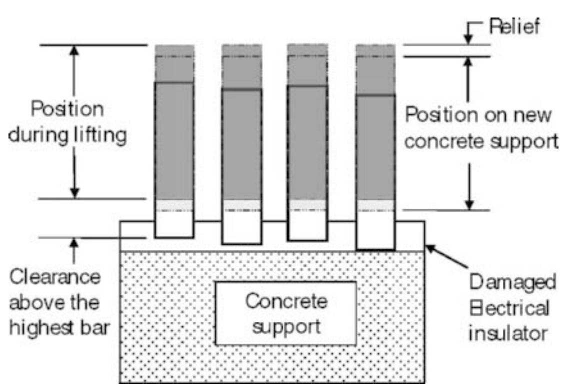

Figure –Busbars Lifting Concept

This meant that bars at lower elevation would be subjected to larger displacements and stresses. The resulting effects on the weld plates and at the interfaces between the cross-over busbars and the potroom input and output circuits were of concern. It was decided to study this further during the FEL3 engineering phase.

Optimal Lifting Sequence and Technical Risks Mitigation Measures Design using FEA

Measurement Program

A measurement program for busbars position and temperatures was put in place for all three potlines cross-overs. The elevation and position of all bars were recorded, as shown in Figure .

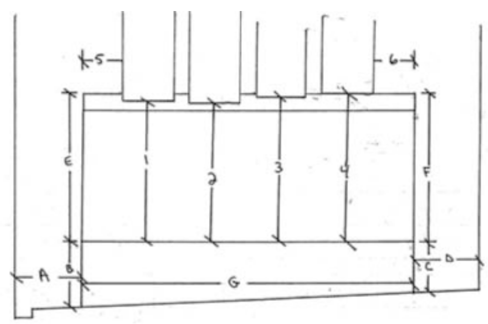

Figure –Busbar Position Measurement Program

The obtained data was used extensively in the Finite Element Analysis of the busbars lifting, as explained in the next section.

Finite Element Analysis

The objectives of the Finite Element Analysis were the following:

- Determine the design loads for the equipment required to mitigate the risks of busbars movement when lifting due to potential residual stresses;
- Determine how to minimize load transfer on weld plates at the interfaces between the cross-over busbars and the potroom input and output circuits when lifting;
- Optimize the lifting sequence, the maximum bar vertical displacement and the relief, for minimal stresses on the busbars systems.

As a first task, it was assumed that bars were prevented from moving by being sunk into the insulation, which provides an upper bound for the residual stresses. A thermo-elastic simulation with prescribed displacements as per the measurement campaign at the location of the supports was made. The reactions at the displacement boundary conditions were used to extract the design loads for the lateral supports.

However, it was reasoned and tested with a simple cantilever beam model that stresses at lifting were maximum when assuming that bars sunk into the insulation were now plastically deformed and that long-term exposure to elevated temperatures had relaxed the stresses to an essentially thermo-elastic condition. The lifting analyses were therefore performed using this approach.

Referring to Figure , the "stress-free" deformed reference configuration (C*) from the measured configuration (C_M), thermal expansion had to be taken out of the equation. A thermal-electrical model based on the approach detailed in [1] and validated on the temperature measurements was built to calculate the thermo-elastic (C_{TE}) based on the nominal configuration (C_0).

A permanent deformation vector (Δu^P) was calculated and then applied to the reference configuration (C_0) to obtain C*.

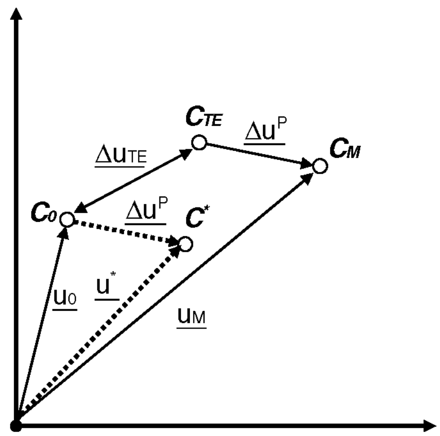

Figure –Representation of Reference Configurations

C_0	Nominal configuration
C_{TE}	Nominal configuration thermo-elastically deformed
C_M	Measured configuration
C^*	Permanently deformed relaxed configuration
$\underline{u_0}$	Nominal position
$\underline{u_M}$	Measured position
$\underline{u^*}$	Permanently deformed relaxed position
$\underline{\Delta u_{TE}}$	Thermo-elastic displacement
$\underline{\Delta u^P}$	Permanent deformation
In C_M	$\underline{u_M} = \underline{u_0} + \underline{\Delta u_{TE}} + \underline{\Delta u^P}$, *i.e.* $\underline{\Delta u^P} = (\underline{u_M} - \underline{u_0}) - \underline{\Delta u_{TE}}$, and
In C^*	$\underline{u^*} = \underline{u_0} + \underline{\Delta u^P}$

The busbars were represented by solid elements. Plate welds were considered to be solids, i.e. the rigidity of the plate welds is assumed to be sufficiently close to a full solid cross-section to provide adequate prediction of the global behavior of the system. For the same reasons, the connection at the interfaces between the cross-over busbars and the potroom input and output circuits were also assumed to be on the full cross-section. The detailed stress distribution of plate welds and connections were determined using sub models taking into account each plate, contact between plates and the geometry of the actual welds. An example of a sub model mesh on the global mesh is shown in Figure .

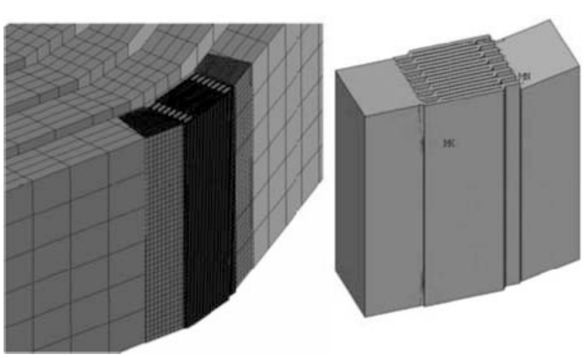

Figure –Plate Weld Sub model Example

Interactions between busbars and supports were taken into account using contact mechanics including frictional sliding. The concrete supports themselves were neglected and represented for each bar by a rigid target surface at the proper elevation.
The expansion joint in the middle of the cross-over was represented by a uniaxial non-linear spring element with a different rigidity in tension and in compression. The out-of-plane lateral displacements at the interface between the non-linear spring and the busbar solid elements were coupled to represent the stiffness in out-of-plane bending. The vertical displacements were not coupled, which represents a vertically flexible joint. The non-linear spring stiffness was calculated by an expansion joint mechanical sub model.

The following procedure was used for the analysis of busbars lifting sequences:

1. Thermal-electrical simulation at conditions when the measurements were performed;
2. Free expansion thermal-mechanical simulation calculation using nominal geometry (C_0) and temperature field from 1 (obtain C_{TE} : $\underline{u_0} + \underline{\Delta u^{TE}}$);
3. Calculation of required additional displacements ($\underline{\Delta u^P}$) to reflect the measured positions ($\underline{u_M}$) (*i.e.* $\underline{\Delta u^P} = (\underline{u_M} - \underline{u_0}) - \underline{\Delta u_{TE}}$);
4. Morphing of the busbar mesh using the additional displacements from 3 ($\underline{\Delta u^P}$);
5. Assembly of permanently deformed system (from 4, obtain C^* : = $\underline{u_0} + \underline{\Delta u^P}$);
6. Thermal-electrical simulation for winter conditions at the time of the project execution
7. Free expansion thermal-mechanical simulation calculation using permanently deformed geometry (C^*) from 5 and temperature field from 6;
8. Thermal-mechanical lifting strategy simulation;
9. Selected plate welds submodeling using global displacements from 8;
10. Selected busbar to interface with input and output circuits submodeling using global displacements from 8.

The maximum bar vertical displacement and subsequent relief were determined using the model for lifts inside the tunnel. Using detailed sub models (Figure), it was confirmed that joints with weld plates would be able to sustain the lifting.

However, it was confirmed that excessive stresses could be generated at the interfaces between the cross-over busbars and the potroom input and output circuits when lifting the busbars at the supports outside the tunnel, particularly in the welds. Fortunately, there was space and access for these supports, such that a new strategy was defined. The new supports would be positioned in contact with the busbars besides the old ones. In case of different busbar elevation on a support, aluminium shims would be screwed in the busbars to form a level plane, and then the old supports would be cut and removed using a diamond-wire.

The model was also used to determine that bending and torsion loads on weld plates at the interfaces between the cross-over busbars and the potroom input and output circuits when lifting the busbars inside the tunnel could be minimized by creating fixed points close to the critical weld plates, which forced displacements towards the expansion joint in the middle of the tunnel.

Specialized Tooling

Lifting Table

A floating potential lifting table was designed for the project. The design loads were obtained from the Finite Element Analysis. The table consists of an aluminium frame supporting a twin Kevlar inflatable bags arrangement pushing on a guided aluminium plate when filled with compressed air. This plate is topped with an electrical insulation board to contact the busbars. The table legs are insulated. The Kevlar bags are controlled by a pressure regulator allowing very precise lifting of the busbars. The table is shown in position inside the tunnel on Figure .

Figure – Floating Potential Lifting Table

Lateral Supports

Floating potential lateral supports were designed to protect the flexible joints in the middle of the tunnel by preventing lateral movement of the busbars once lifted from the old supports. The design loads were obtained from the Finite Element Analysis. Aluminium tubes with stainless steel machine screw actuated adjustable insulated contact pads were positioned to be in contact with the tunnel floor, ceiling and wall while applying a small pressure on the busbars. The supports are shown in position inside the tunnel on Figure . The contact pads with walls, floor and ceiling are also insulated. The lateral supports were designed with easy assembly and dismantling for relocation in mind. Note the yellow electrical insulation covering the busbars.

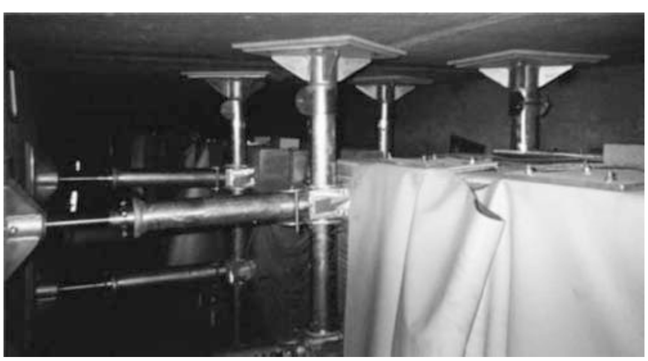

Figure – Floating Potential Lateral Supports

Fixed Point Supports

To prevent transfer of bending and torsion loads on weld plates at the interfaces between the cross-over busbars and the potroom input and output circuits when lifting the busbars, so-called "fixed point supports" were built. The design loads were obtained from the Finite Element Analysis. Aluminium tubes with stainless steel machine screw actuated adjustable insulated contact pads were positioned to be in strong positive contact with the potroom basement floor and ceiling. The supports are shown in position in the potroom basement on Figure . Note the yellow electrical insulation covering the busbars.

Figure – Floating Potential Fixed-Point Supports

Handling Cart for New Supports

A light stainless steel structure with wheels, shown on Figure , was designed to fit on the new supports for easier handling of the new supports in the tunnel.

Figure – Prefabricated Support with Bogey for Handling

Insulation Replacement Project Execution

A commitment to Health & Safety is a shared value for all the parties involved in the project, and an attention to safety in design and on site via a collaborative approach with contractors is critical in achieving "Zero harm", in addition to management tools and systems during the execution phase.

Detailed specifications for executing the work were therefore developed with ABI and the selected contractors. In-depth analysis of the risks for each task was performed and work procedures were developed ensuring health & safety of the workers. Work sequencing was performed to minimize work inside the tunnels and idle time. Before the go ahead was given for construction, a final risk analysis was performed to ensure all risks were properly mitigated and controlled.

The first task was to install electrical protection on the busbars to prevent accidental contact. Then, once the lateral and fixed point supports were installed, the new supports were positioned besides the old ones using the bogeys.

Starting from the center and moving towards one end of the tunnel, a team of three workers inside the tunnel used the lifting table to lift the busbars besides the old support, push the old one in the alley using Kevlar bags actuated with compressed air, position the new support at the same location than the old one and at the proper elevation and then bring the busbars down on the new support. In parallel, a second team of two workers used a winch installed outside the potroom and a nylon cable to drag the old supports out of the tunnel. The sequence was repeated for the other half of the tunnel. Once all the supports had been replaced, an epoxy-based grout was used to secure the supports in place. Pictures of the main tasks are shown in Figure , while the old supports are shown in Figure , and the new ones, in Figure .

a) Busbars Lifted from Old Supports

b) Pushing the Old Support into Alley using Kevlar Bag

c) Pulling the Old Support along Tunnel Alley

Figure – Work Inside the Tunnels

Figure – Old Cross-Over Busbar Supports

Figure – New Cross-Over Busbar Support in Place

Outside the tunnels, the supports were replaced according to the strategy of positioning the new supports in contact with the busbars besides the old ones, using aluminium shim to create a level plane, and then cutting the old supports using a diamond-wire.

The work was executed successfully with no incident, no damage and no cut-out while on schedule and below budget.

Permanent Tunnel Forced-Cooling

Once the insulation had been replaced, the permanent tunnel forced-cooling project was executed. The basic concept is to use the tunnel as a duct such that fresh air is forced inside the tunnel at the ends and hot air is extracted in the middle. Computational Fluid Dynamics was used extensively in the design process for sizing the fans and designing the extraction fan inlet for minimal pressure loss.

Conclusions

The project team was faced with the challenge of replacing electrical insulation in cross-over tunnels while the busbars were energized. Experience and expertise of the ABI smelter, the original technology supplier Aluminium Pechiney, Alcoa and Hatch were fully utilized in the development of an optimized project scope. Key factors for success were risk analysis and mitigation, attention to safety in design and on site via a collaborative approach with contractors, and the use of advanced engineering tools like Finite Element Analysis to support risk assessment and mitigation and for detailed design.

References

[1] A.F. Schneider, D. Richard and O. Charette, “Impact of Amperage Creep on Busbars and Electrical Insulation: Thermal-Electrical Aspects”, Proc. Light Metals 2011, TMS, Warrendale, PA, pp 525-530.